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Chapter 19

THREE PHASE INDUCTION GENERATORS

19.1 INTRODUCTION

In Chapter 7 we alluded to the induction generator mode both in stand alone (capacitor excited) and grid-connected situations. In essence for the cage-rotor generator mode, the slip S is negative ($S < 0$). As the IM with a cage rotor is not capable of producing, reactive power, the energy for the machine magnetization has to be provided from an external means, either from the power grid or from constant (or electronically controlled) capacitors.

The generator mode is currently used for braking advanced PWM converter fed drives for industrial and traction purposes. Induction generators-grid connected or isolated (capacitor excited)-are used for constant or variable speed and constant or variable voltage/frequency, in small hydro power plants, wind energy systems, emergency power supplies, etc. [1]. Both cage and wound rotor configurations are in use. For a summary of these possibilities, see [Table 19.1](#). Cogeneration of electric power in industry at the grid (constant voltage and frequency) for low range variable speed and motor/generator operation in pump-back hydropower plant are all typical applications for wound rotor IMs.

In what follows, we will treat the main performance issues of IGs first in stand alone configurations and then at power grid. Though changes in performance owing to variable speed are a key issue here, we will not deal with power electronics or control issues. We choose to do so as IG systems now constitute a mature technology whose in-depth (useful) treatment could be the subject matter of an entire book.

Table 19.1 IG configurations

IG type	speed		grid	isolated	frequency		voltage	
	constant	variable	connected		constant	variable	constant	variable
wound rotor	-	*	*	-	*	-	*	-
cage rotor	*	*	*	*	*	*	*	*

-impractical; * practical;

Typical configurations of IGs are shown in [Figure 19.1-19.4](#).

[Figure 19.1](#) portrays a WR-IG whose rotor is connected through a bi-directional power flow converter and transformer to the power grid which has constant voltage and frequency.

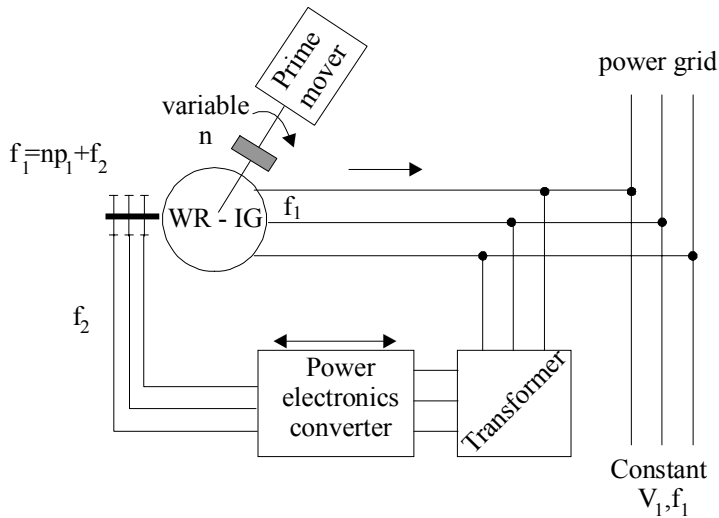


Figure 19.1 Advanced (bi-directional rotor power flow) wound rotor IG (WR - IG) at power grid

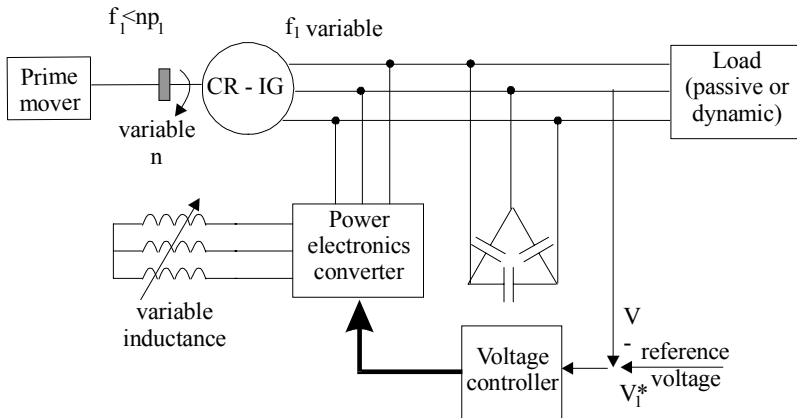


Figure 19.2 Isolated cage-rotor IG (CR - IG) with constant voltage V_1 and variable frequency output f_1 for variable speed

For limited prime mover speed variation ($X\%$), the power converter rating is limited to $X\%$ of IG rated power. Consequently reasonably lower costs are encountered.

Figure 19.2 shows an isolated cage-rotor IG (CR - IG) with variable frequency but constant voltage for variable prime mover speed. The power electronics converter in Figure 19.2 has limited rating and simplified control as it acts as a Variac to control (reduce) the capacitance reactive power flow into the IG for constant voltage control.

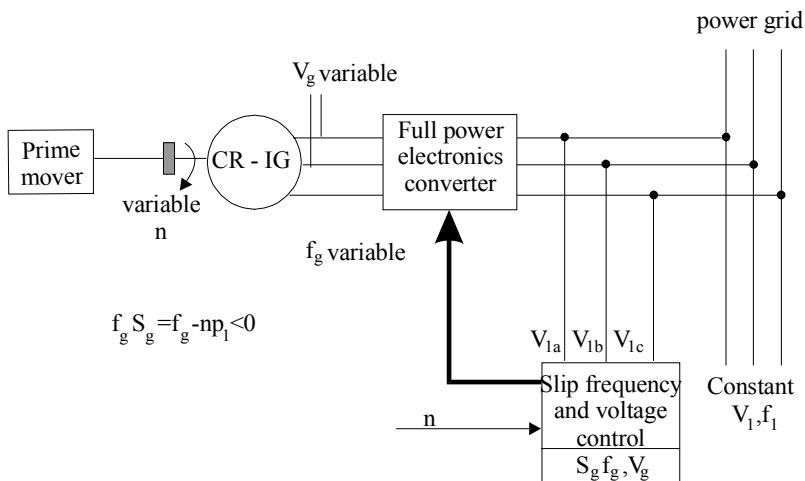


Figure 19.3 Power grid connected CR-IG variable speed constant V_1 & f_1

The a.c.-a.c. power electronics converter (PEC) in Figure 19.3 makes the transition from the variable voltage and frequency V_g, f_g of the generator to the constant voltage and frequency of the power grid. In the process, the same PEC transfers reactive power from the power grid to provide the magnetization of the cage-rotor induction generator (CR - IG).

The PEC is rated at full power and thus adds to the total costs of the equipment while the CR-IG is rugged and costs less.

Handling limited variable speed prime movers (wind or constant head small hydraulic turbines) to extract most of the available primary energy may be done by simpler methods such as pole changing windings for CR-IG (Figure 19.4a) or even a parallel connected R_{ad}/L_{ad} circuit in the rotor of the WR-IG for grid connected IGs (Figure 19.4b).

On the other hand, for less frequency sensitive loads voltage regulation for variable speed variable frequency but constant voltage, long shunt capacitor connections or saturable load interfacing transformers may be used in conjunction with CR-IGs.

Solutions like those shown in Figure 19.4 are characterized by low costs. But the power flow control and voltage regulation (for isolated systems) are only moderate. For low/medium power applications with limited primer mover speed variation they are adequate.

The system configurations presented in Figures 19.1-19.4 are meant to show the multitude of solutions that are feasible and have been proposed. Some of them are extensively used in wind power and small hydropower systems.

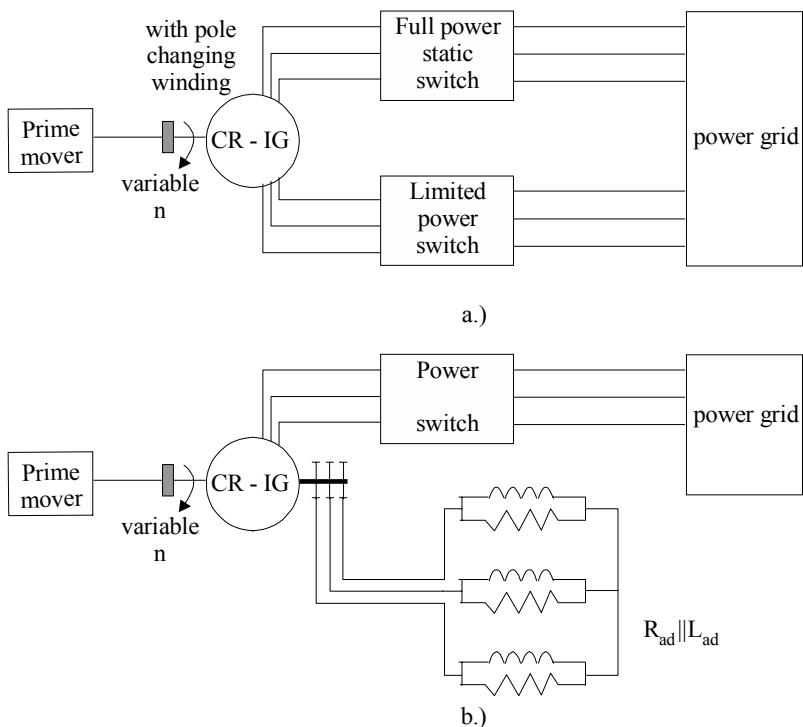


Figure 19.4 Simplified IG systems

- a.) CR-IG with pole changing winding and two static power switches for grid connection
b.) WR-IG with parallel $R_{ad} \parallel L_{ad}$ in the rotor for grid connection system

In the following we will focus on IG behavior in such schemes rather than on the systems themselves. We will first investigate in depth the self excitation and load performance steady state and transients of CR-IG with capacitors for isolated systems.

Then the WR-IG with bi-directional power capability PEC in the rotor for grid connected systems will be dealt with in some detail in terms of stability limits and performance.

19.2 SELF-EXCITED INDUCTION GENERATOR (SEIG) MODELING

By SEIG, we mean a cage-rotor IG with capacitor excitation (Figure 19.5a). The standard equivalent circuit of SEIG on a per phase bases is shown in Figure 19.5b.

First, with the switch S open, the machine is driven by the prima mover. As the SEIG picks up speed slowly, the no load terminal voltage increases and settles at a certain value. This is the self-excitation process, which has been known from 1930s. [2]

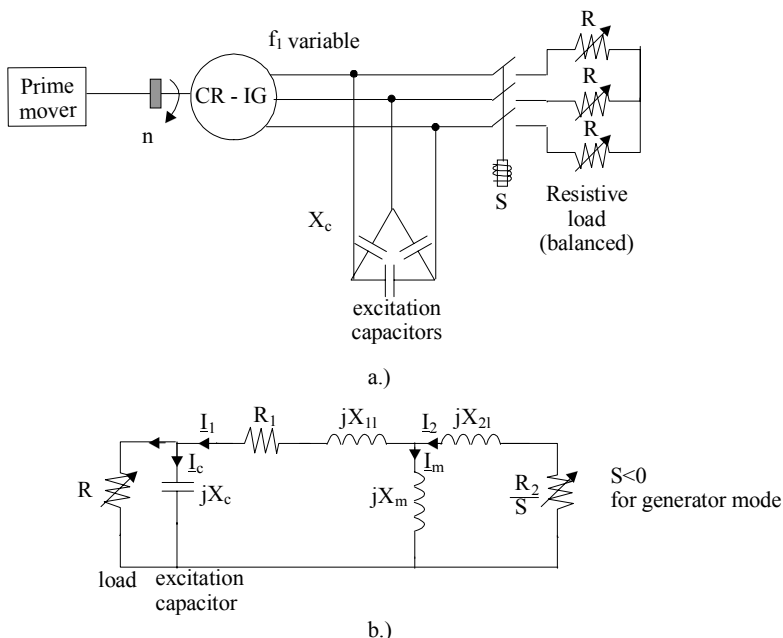


Figure 19.5 Selfexcited induction generator (SEIG) with resistive load
a.) general scheme; b.) standard equivalent circuit

In essence, first the residual magnetism in the rotor laminated core (from previous IG operation) produces by motion an e.m.f. in the stator windings. Its frequency is $f_{10} = np_1$. This e.m.f. is applied to the machine terminals and produces in the RLC circuit of each phase a magnetization current which produces an airgap field. This field adds to the remnant field of the rotor to produce a higher e.m.f.. The process goes on until an equilibrium is reached for a given speed n and a given capacitance C at a voltage level V_0 . However this process is stable as long as the machine is saturated $X_m(I_m)$ is a nonlinear function (as shown already in Chapter 7).

In a very simplified form, with X_{1l} , X_{2l} , R_1 , R_2 -neglected, the equivalent circuit for no load degenerates to X_m in parallel with a capacitor and a small e.m.f. determined by the remnant rotor field (Figure 19.6a).

The mandatory nonlinear $L_m(I_m)$ relationship is evident from Figure 19.6b where the final no load voltage V_{10} occurs at the intersection of the no load characteristic (to be found by the standard no load test, or by design)-with the capacitor voltage straight line. Also the necessary presence of remnant rotor field (E_{rem}) is self evident.

Once the SEIG is loaded, the terminal voltage changes depending on speed, SEIG parameters, the nature of the load and its level.

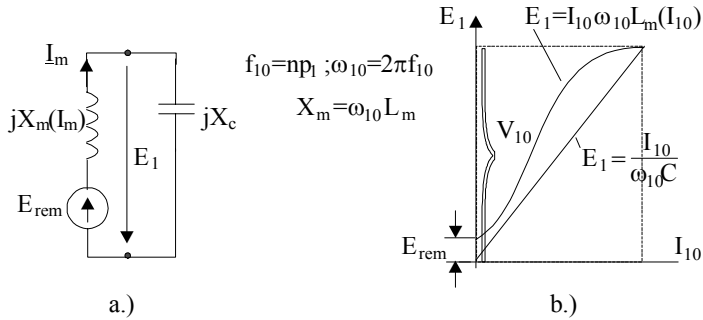


Figure 19.6 Oversimplified circuit for explaining self-excitation
a.) the circuit, b.) the characteristics

The occurrence of load implies rotor currents, that is a non zero slip, $S \neq 0$. Even if the speed of the prime mover is kept constant, the frequency f_1 varies with load

$$f_1 = \frac{np_1}{1+|S|}; \quad f_{10} = (f_1)_{S=0} = np_1 \quad (19.1)$$

Calculating the variation of voltage V_1 , frequency f_1 , stator current I_1 , power factor, efficiency, with speed n , load and capacitor C , means, in fact, to determine the steady state performance of SEIG. In this arrangement, V_1 and f_1 are fundamental unknowns.

It is also feasible to have the capacitance C and frequency f_1 as the main unknowns for given speed, load and output voltage V_1 . Apparently the problem is simple use the standard circuit of Figure 19.5b with given $L_m(I_m)$ function. The next paragraph deals extensively with this issue.

19.3 STEADY STATE PERFORMANCE OF SEIG

Various analytical methods (models) have been developed in order to predict the steady state performance of SEIG.

Among them, two are predominant

- the impedance model;
- the admittance model;

The impedance model is based on the single phase equivalent circuit shown in Figure 19.5a, which is expressed in per unit terms

f-frequency f_1 /rated frequency f_{1b} $f = f_1/f_{1b}$;

v-speed/synchronous speed for f_{1b} $v = np_1/f_{1b}$.

The final form of the circuit is shown in Figure 19.7.

The R , L character of the load, the presence of core loss resistance R_{core} (which may also vary slightly with frequency f), the nonlinearity of $X_m(I_m)$ dependence with the unknowns X_m (the real output is V_1) and f makes the solving of this model possible only through a numerical procedure. Once X_m

and f are calculated, the entire circuit model may be solved in a straightforward manner.

Fifth or fourth order polynomial equations in f or X_m are obtained from the conditions that the real and imaginary parts of the equivalent impedance are zero. A wealth of literature on this subject is available [3–5]. Recently a fairly general solution of the impedance model, based on the optimisation approach has been introduced. [6]

However, the high order of system nonlinearity prevents an easy understanding of performance sensitivity to various parameters. In search of a simpler solution, the admittance model has been proposed. [7]

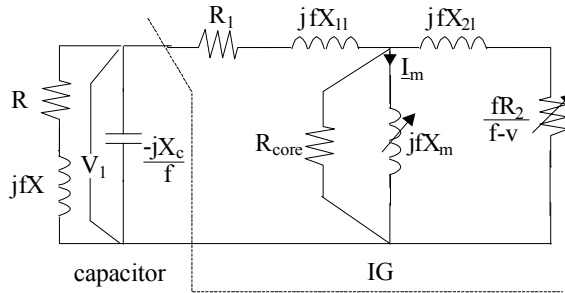


Figure 19.7 The impedance model of SEIG
 f -p.u. frequency, v = p.u. speed.

While the X_m equation is simple, calculating f involves a complex procedure. In [8, 9] admittance models that lead to quadratic equations for the unknowns are obtained for balanced resistive load without additional simplifying assumptions.

19.4 THE SECOND ORDER SLIP EQUATION MODEL FOR STEADY STATE

The second order equation model may be obtained from the standard circuit shown in Figure 19.8.

The slip is negative for generator mode

$$S = \frac{(f - v)}{f} \quad (19.2)$$

The airgap voltage E_a for frequency f (in p.u.)

$$\underline{E}_a = f \underline{E}_1 = \underline{I}_2 \left(\frac{R_2}{S} + jX_{21} \right) \quad (19.3)$$

E_1 -airgap voltage at rated frequency.

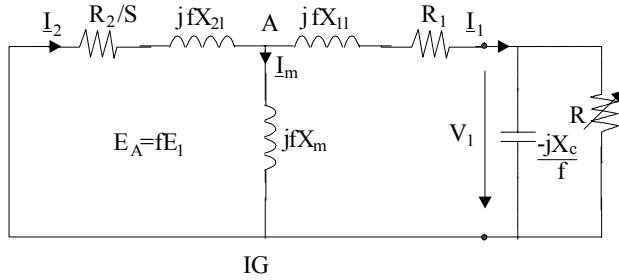


Figure 19.8. Equivalent circuit of SEIG with slip S and frequency f (p.u.) shown

For simplicity, the core loss resistance is neglected while the load is purely resistive. The parallel capacitor-load resistance circuit may be transformed into a series one as

$$R_L - jX_L = \frac{R \left(-j \frac{X_C}{f} \right)}{R - j \frac{X_C}{f}} = \frac{R}{1 + \frac{R^2 X_C^2}{f^2}} - \frac{j \frac{X_C}{f}}{1 + \frac{X_C^2}{f^2 R^2}} \quad (19.4)$$

Now we may lump R_1 and R_L into $R_{1L} = R_1 + R_L$ and fX_{11} and X_L into $X_{1L} = fX_{11} - X_L$ to obtain the simplified equivalent circuit in [Figure 19.9](#).

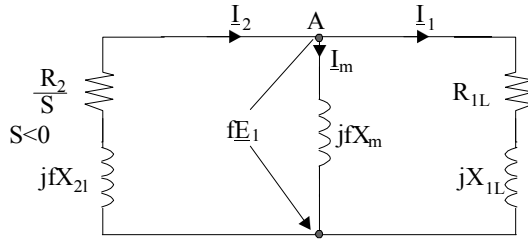


Figure 19.9 A simple nodal form of SEIG equivalent circuit

Notice that frequency f will be given and the new unknowns are S and X_m while $E_1(I_m)$ or $X_m(E_1)$ come from the no load curve of IG. Also the load resistance R , the capacitance C , and the values of R_2 , X_{21} , R_1 , X_{11} are given. Consequently, with f known and S calculated, the speed v will be computed as

$$v = f(1-S) \quad (19.5)$$

If the speed is known, a simpler iterative procedure is required to change f until the desired v is obtained.

We should mention that, with given f , the presence of any type of load does not complicate the problem rather than the expressions of R_L and X_L in (19.4). An induction motor load is such a typical dynamic load.

For self-excitation, the summation of currents in node A (Figure 19.9) must be zero (implicitly $E_1 \neq 0$)

$$0 = -I_2 + I_1 + I_m; \quad (19.6)$$

$$fE_1 \left(\frac{1}{jfX_m} + \frac{1}{R_{1L} + jX_{1L}} + \frac{S}{R_2 + jSfX_{2L}} \right) = 0 \quad (19.7)$$

The same result is obtained in [9] after introducing a voltage source in the rotor.

The real and imaginary parts of (19.7) must be zero

$$\frac{R_{1L}}{R_{1L}^2 + X_{1L}^2} + \frac{SR_2}{R_2^2 + S^2f^2X_{2L}^2} = 0 \quad (19.8)$$

$$\frac{1}{fX_m} - \frac{X_{1L}}{R_{1L}^2 + X_{1L}^2} + \frac{SfX_{2L}}{R_2^2 + S^2f^2X_{2L}^2} = 0 \quad (19.9)$$

For a given f load and IG parameters, (19.8) has the slip S as the only unknown

$$aS^2 + bS + c = 0 \quad (19.10)$$

with $a = f^2X_{2L}^2R_{1L}$; $b = +R_2(R_{1L}^2 + X_{1L}^2)$; $c = R_{1L}R_2^2$ (19.11)

Equation (19.10) has two solutions but only the smaller one (S_1) refers to a real generator mode. The larger one refers to a braking regime (all the power is consumed in the machine losses).

$$S_{1,2} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} < 0 \quad (19.12)$$

Complex solutions $S_{1,2}$ imply that self excitation cannot take place.

Once S_1 is known, the corresponding speed v , for a given frequency f , capacitance and load, is calculated from (19.5). When the speed is given, f is changed until the desired speed v is obtained.

Now, with S , f , etc. known, the only unknown in (19.9) is X_m , which is given by

$$X_m = \frac{R_2(R_{1L}^2 + X_{1L}^2)}{-(SfX_{2L}R_{1L} + R_2X_{1L}f)}; \quad S < 0 \quad (19.13)$$

With X_m determined, E_1 may be directly obtained from the no load curve at the rated frequency (Figure 19.10).

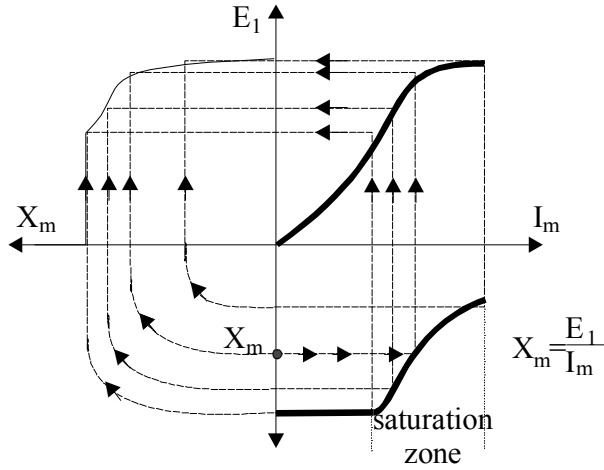


Figure 19.10 No-load curve of IG at rated frequency

As $\underline{E}_1$ and f , S , X_m are known, from the parallel equivalent circuit of [Figure 19.8](#), we may simply calculate $\underline{I}_2$ and $\underline{I}_1$, as I_m comes directly from the magnetization curve ([Figure 19.10](#))

$$\underline{I}_2 = \frac{-f\underline{E}_1}{\frac{R_2}{S} + jfX_{21}} \quad (19.14)$$

$$\underline{I}_1 = \frac{f\underline{E}_1}{R_{1L} + jX_{1L}}; X_{1L} < 0 \quad (19.15)$$

It is now simple to construct the terminal voltage phasor $\underline{V}_1$ as

$$\underline{V}_1 = \underline{I}_1 [(R_{1L} - R_1) + j(X_{1L} - X_{11})] \quad (19.16)$$

or

$$\underline{V}_1 = f\underline{E}_1 - (R_1 + jfX_{11})\underline{I}_1 \quad (19.17)$$

Capacitor and load currents, I_C and I_L are, respectively,

$$\underline{I}_C = +\underline{V}_1 jf / X_C; \quad \underline{I}_L = \underline{I}_1 - \underline{I}_C \quad (19.18)$$

Equations (19.14)-(19.18) are illustrated on the phasor diagram of [Figure 19.11](#).

As the direction of the stator current, $\underline{I}_1$, and voltage, $\underline{V}_1$, have been chosen for the generator, φ_1 -the power factor angle shows the current ahead of voltage. This is a clear sign that the machine is magnetised from outside.

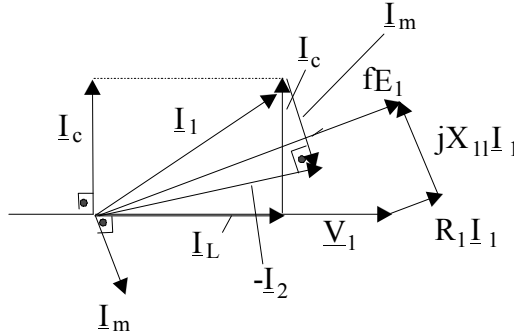


Figure 19.11. SEIG phasor diagram under resistive load

As expected, for a resistive load, the terminal voltage $\underline{V}_1$ and the load current $\underline{I}_L$ end up in phase (Figure 19.11). We may approximately calculate the core losses, p_{core} , as

$$p_{\text{core}} = \frac{3(fE_1)^2}{R_{\text{core}}} \quad (19.19)$$

with R_{core} determined from no load tests at the rated frequency. In reality R_{core} varies slightly with frequency and a no load test for different frequencies would give the $R_{\text{core}}(f)$ functional.

The SEIG efficiency η_g is

$$\eta_g = \frac{3V_1 I_L \cos \phi_L}{3V_1 I_L \cos \phi_L + 3R_1 I_1^2 + 3R_2 I_2^2 + p_{\text{core}} + p_{\text{mec}}} \quad (19.20)$$

Mechanical losses are determined separately from the standard no load tests at variable voltage and, eventually, frequency.

As we can see the direct steady state problem with f_1 and capacitance given (and the load) machine parameters and no load characteristic given and S and X_m as unknowns, may be solved in a straightforward manner. In the case when the speed v , instead of f , is fixed, the problem may be solved the same way through a few iterations by changing f in (19.10) until the value of $S < 0$ will produce the required speed $v = f(1-S)$.

The solution to (19.10) leads to a few solution existence conditions

$$fX_{1l} < X_L; \quad X_L = \frac{\frac{X_C}{f}}{1 + \frac{X_C^2}{f^2 R^2}} \quad (19.21)$$

where X_L refers to the capacitor in parallel with the load impedance.

Without capacitive predominance, the voltage collapses. With given X_C (capacitor), (19.21) reduces to a load resistance R condition given by

$$R \geq X_C \sqrt{\frac{X_{1l}}{X_C - f^2 X_{1l}}} \quad (19.22)$$

The load resistance R has to be a real number in (19.22)

$$X_C \geq f^2 X_{1l} \quad (19.23)$$

Thus, (19.22) sets the value of the minimum load resistance $R_{\min}$ for a given capacitance, frequency f and stator leakage reactance X_{1l} . The smaller the X_{1l} , the lower the $R_{\min}$, that is, the larger the maximum load.

Also the slip equation (19.10) solutions must be real such that

$$b^2 - 4ac = R_2^2 (R_{1l}^2 + X_{1l}^2)^2 - 4f^2 X_{2l}^2 R_{1l}^2 R_2^2 > 0 \quad (19.24)$$

or

$$2fX_{2l} \leq \frac{(R_{1l}^2 + X_{1l}^2)}{R_{1l}} \quad (19.25)$$

A low rotor leakage reactance X_{2l} seems beneficial from this point of view.

The maximum possible value of the slip $S_{\max}$ corresponds to $b^2 - 4ac = 0$, and from (19.12) with (19.25), it becomes

$$S_{\max} = -\frac{b}{2a} = -\frac{R_2}{fX_{2l}} \quad (19.26)$$

For this limiting value of the slip (19.21) is not satisfied and more. So the composite capacitor-load reactance is not capacitive any more. Consequently, the voltage collapses at $S_{\max}$. However, the elegant expression (19.26), which corresponds essentially to an ideal maximum load power, represents a design constraint condition. We may remember that $S_{\max}$ of (19.26) corresponds to the peak torque slip of constant airgap flux vector controlled induction machine [10].

Example 19.1 The slip S and X_m problem solution.

Let us consider an IM with the data $P_n = 7.36$ kW, $f_{1b} = 60$ Hz, $2p_1 = 2$ poles, star-connection, $V_{1n} = 300$ V stator resistance $R_1 = 0.148$ Ω , rotor resistance $R_2 = 0.144$ Ω , stator leakage reactance (at 60Hz) $X_{1l} = 0.42$ Ω , the rotor leakage reactance $X_{2l} = 0.25$ Ω and the no load curve $E(X_m)$ at 60 Hz (Figure 19.10) may be broken into a few straight line segments. [9]

$$E_1 = \begin{cases} 0; & X_m \geq 24.0\Omega \\ 304.1 - 7.67X_m; & 19 \leq X_m \leq 24 \\ 220 - 3.16X_m; & 16 \leq X_m \leq 19 \\ 206 - 2.17X_m; & X_m < 16 \end{cases} \quad (19.27)$$

Let us determine the voltage and speed for $f_g = 43.33$ Hz and for $f_g = 58.33$ Hz and zero load ($R = \infty$).

Solution

We start with a given frequency for no load $R = \infty$ in (19.4), with $f \approx 43.33/60 \approx 0.722$, $R_L = 0$, $X_L = X_C/f$, $R_{IL} = R_1 + R = R_1 = 0.148\Omega$.

$$X_{IL} = fX_{II} - \frac{X_C}{f} = 0.722 \cdot 0.42 - \frac{1}{2\pi 60 \cdot 0.722 \cdot 180 \cdot 10^{-6}} \approx -20.11\Omega$$

Now from (19.11) a, b, c are

$$a = f^2 X_{21}^2 R_{IL} = 0.722^2 \cdot 0.25^2 \cdot 0.148 = 4.821 \cdot 10^{-2}$$

$$b = R_2 (R_{IL}^2 + X_{IL}^2) = 0.144 \cdot (0.148^2 + 33.42^2) = 160.833$$

$$c = R_{IL} R_2^2 = 0.148 \cdot 0.144^2 = 3.069 \cdot 10^{-3}$$

From (19.12)

$$S_1 = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

For $4ac \ll b$, we may approximate S_1 by

$$S_1 = \frac{-2ac}{2ab} = -\frac{c}{b} = \frac{3.069 \cdot 10^{-3}}{2 \cdot 160.33} \approx 1 \cdot 10^{-5} \approx 0$$

This small value was expected.

From (19.13) the magnetization reactance is

$$X_m = \frac{R_2 (R_{IL}^2 + X_{IL}^2)}{-R_2 X_{IL} f} \approx \frac{-X_{IL}}{f} = \frac{20.11}{0.722} = 27.864 > 24.0\Omega$$

with zero rotor current X_m is expected to be fully compensated by the capacitance reactance minus the stator leakage reactance. The e.m.f. value E_1 , for $X_m = 27.864 > 24$ in (19.27), is $E_1 = 0$, that is, at a low frequency (speed), with a capacitance $C = 180\mu F$ (per phase) the machine does not self excite even on no load!

For $f_g = 58.33\text{Hz}$ ($f = 0.9722$), however, and $R = \infty$, X_{IL} becomes

$$X_{IL} = fX_{II} - \frac{X_C}{f} = 0.9722 \cdot 0.42 - \frac{1}{2\pi 60 \cdot 0.9722 \cdot 180 \cdot 10^{-6}} = -14.75\Omega$$

In this case
$$X_m = -\frac{X_{IL}}{f} = -\frac{14.75}{0.9722} = 15.179\Omega$$

Now from (19.27)

$$E_1 = 206 - 2.27 \cdot 15.179 = 171.54V$$

The phase current I_1 (equal, in this case, to capacitor current) is (from (19.15))

$$I_1 = \frac{fE_1}{R_{IL} + jX_{IL}} = \frac{0.9722 \cdot 171.54}{0.148 - j14.75} = 1.13 \cdot 10^{-2} + j11.306$$

The terminal voltage $\underline{V}_1$ (from 19.17) is

$$\begin{aligned} \underline{V}_1 &= fE_1 - (R_1 + jfX_{IL})I_1 = \\ &= 0.9722 \cdot 171.54 - (0.148 + j0.9722 \cdot 0.42)(1.13 \cdot 10^{-2} + j11.306) = \\ &= 171.422 - j1.67 \end{aligned}$$

Due to capacitor current (V_1) > fE_1 as expected. Note also that with $S = 0$, $I_2' = 0$.

When the machine is loaded ($R = 40\Omega$), as expected, at $f = 43.33\text{Hz}$ and same capacitor, the machine again will not self-excite (it did not under no load).

However, for $f = 58.33\text{Hz}$ it may self-excite.

With $R = 40\Omega$ and $X_C = \frac{1}{2\pi 60 \cdot 180 \cdot 10^{-6}} = 14.744\Omega$ from (19.4)

$$R_L = \frac{R}{1 + \frac{R^2}{X_C^2}} = \frac{40}{1 + \frac{40^2 \cdot 0.9722^2}{14.744^2}} = 5.027\Omega$$

$$X_L = \frac{\frac{X_C}{f}}{1 + \frac{X_C^2}{R^2 f^2}} = \frac{\frac{14.744}{0.9722}}{1 + \frac{14.744^2}{0.9722^2 \cdot 40^2}} = 13.26\Omega$$

So,

$$\begin{aligned} R_{IL} &= R_1 + R_L = 0.148 + 5.027 = 5.175\Omega \\ X_{IL} &= fX_{IL} - X_L = 0.9722 \cdot 0.42 - 13.26 = -12.851\Omega \end{aligned}$$

The coefficients a, b, c are obtained from (19.11)

$$\begin{aligned} a &= f^2 X_{21}^2 R_{IL} = 0.9722^2 \cdot 0.25^2 \cdot 5.175 = 0.3057 \\ b &= R_2 (R_{IL}^2 + jX_{IL}^2) = 0.144(5.475^2 + 12.551^2) = 27.6377 \\ c &= R_{IL} R_2^2 = 5.175 \cdot 0.25^2 = 0.323 \end{aligned}$$

Still $b^2 \gg 4ac$, so S_1 is

$$S_1 = \frac{-c}{b} = \frac{-0.323}{27.6377} = -1.17 \cdot 10^{-2}$$

Now the speed n is

$$n = f_g (1 - S_1) = 58.33 \cdot (1 + 1.17 \cdot 10^{-2}) = 59.126 \text{ rps} = 3540.75 \text{ rpm}$$

The magnetizing reactance X_m is (19.13)

$$\begin{aligned} X_m &= \frac{R_2(R_{IL}^2 + X_{IL}^2)}{-(SfX_{21}R_{IL} + R_2X_{IL})f} = \\ &= \frac{0.144(5.175^2 + 12.851^2)}{-(-1.17 \cdot 10^{-2} \cdot 0.9722 \cdot 0.25 \cdot 5.175 + 0.144 \cdot (-12.851)) \cdot 0.9722} = 15.241 \Omega \end{aligned}$$

The e.m.f. E_1 is thus (19.27)

$$E_1 = 206 - 2.27 \cdot 15.241 = 171.40 \text{ V}$$

The stator current I_1 (19.15) writes

$$\underline{I}_1 = \frac{fE_1}{R_{IL} + jX_{IL}} = \frac{0.9722 \cdot 171.54}{5.175 - j12.851} = 4.493 + j11.157$$

The terminal phase voltage $\underline{V}_1$ (19.16) is

$$\begin{aligned} \underline{V}_1 &= fE_1 - (R_1 + jfX_{11})\underline{I}_1 = \\ &= 0.9722 \cdot 171.40 - (0.148 + j0.9722 \cdot 0.148)(4.493 + j11.157) = \\ &= 166.729 - j2.29; \quad V_1 = 166.74 \text{ V} \end{aligned}$$

Notice that the terminal voltage decreased from no load to $R = 40 \Omega$ load, from 171.54V to 166.74V, while the speed required for the same frequency $f_g = 58.33 \text{ Hz}$ had to be increased from 3500 rpm to 3540.75 rpm.

The load is still rather small as the output power P_2 is

$$P_2 = 3R_L I_1^2 = 3 \cdot 5.027 \cdot (4.493^2 + 11.157^2) = 2.181 \text{ kW} \ll 7.36 \text{ kW}$$

If the speed v is given, the computation of slip from (19.12) is done starting with a few frequencies lower than the speed until the required speed is obtained.

Once computerized, the rather straightforward computation procedure presented here allows for all performance computation, for given frequency f (or speed), capacitance, load and machine parameters. Any load can be handled directly putting it in form of a series impedance.

The slip and capacitor problem occurs when the voltage V_1 , speed and load are given. To retain simplicity in the computation process, the same algorithm as above may be used repeatedly for a few values of frequency and then for

capacitance (above the no load value at same voltage) until the required voltage and speed are obtained.

The iterative procedure converges rapidly as voltage in general increases with capacitance C .

19.5 STEADY STATE CHARACTERISTICS OF SEIG FOR GIVEN SPEED AND CAPACITOR

The main steady state characteristics of SEIGs are to be obtained at constant (given) speed though a prime mover, such as a constant speed small hydroturbines, does not have constant speed if unregulated.

They are

- Voltage/current characteristic –for given speed and load power factor
- Voltage versus power-for given speed and load power factor
- Frequency (slip) versus load power for given speed and power factor

All these curves may be obtained by using the second order slip equation model.

Such qualitative characteristics are shown in [Figure 19.12a, b, c](#).

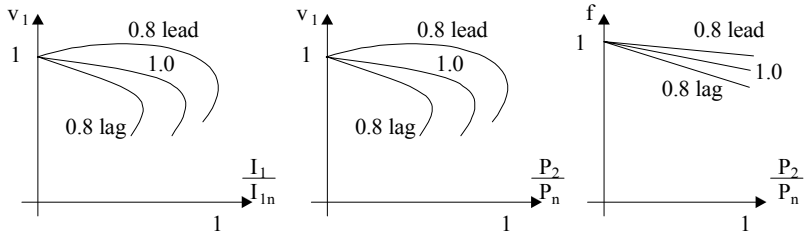


Figure 19.12 Steady state curves for given speed and capacitor
a.) voltage/current, b.) voltage/power, c.) frequency/power

The slight increase and then decrease in output voltage with power (and current) for leading power factor is expected. For lagging power factor, the voltage drops rapidly and thus the critical slip is achieved at lower power levels. The frequency is influenced little by the power factor for given load. On the other hand, for low value of slips, S_1 , from (19.12), becomes

$$S_1 = \frac{-c}{b} = \frac{-R_{IL} R_2}{R_{IL}^2 + X_{IL}^2} \quad (19.28)$$

The larger X_{IL} , the smaller S_1 will be. Note that X_{IL} includes the self excitation capacitance in parallel with the load.

The characteristics notably change if the prime mover speed is not regulated. The same methodology as above may be used, with the speed versus power curve as given, to obtain results as shown in [1].

For constant head hydroturbines, the speed decreases with power and thus the voltage regulation is even more pronounced. Variable capacitance is needed to limit the voltage regulation.

19.6 PARAMETER SENSITIVITY IN SEIG ANALYSIS

By parameter sensitivity to performance we mean the influence of IG resistances R_1 , R_2 and reactances X_{1l} , X_{2l} , X_m and of parallel or series-parallel excitation capacitor on performance.

Parameter sensitivity studies of SEIG may be performed for unregulated (variable speed) [1] or regulated (constant speed) prime movers. [6] The main conclusions of such studies are as follows

For constant speed

- The no load voltage increases with capacitance
- The terminal voltage and maximum output power increase notably with capacitance
- For constant voltage the needed excitation capacitance increases with power
- At no load the magnetisation reactance decreases with the supply voltage increase
- In the stable load area, voltage increases with IG leakage reactance and decreases with rotor resistance

For variable speed (constant head hydroturbine)

- Along a rather large (40%) load resistance variation range, the output power varies only a little
- Within the range of rather constant power the voltage drops sharply with load, more so with inductive-resistive loads
- Up to peak load power the frequency and speed decrease with power. They tend to increase after that which is to be translated into stable operation from this point of view
- The maximum power depends approximately on $C^{2.2}$ [3] and the corresponding voltage on $C^{0.5}$ [11]
- For no load the minimum capacitance requirement is inversely proportional to speed squared
- As expected, under load the minimum required capacitance depends on load impedance, load power factor and speed
- When the capacitance is too small it produces negligible capacitive current for magnetisation and thus the SEIG cuts off. At the other end, with too large a capacitance, the rotor impedance of the generator causes deexcitation and the voltage collapses again. In between there should be an optimal value of capacitance C for which both output power and efficiency are high
- When feeding an IM load the SEIG's power rating should be 2 to 3 times higher than that of the IM and about twice the capacitance needed for a 0.8

lag power factor passive load. These requirements are mainly imposed by the IM transients during starting. [12]

- The long shunt connection decreases the voltage regulation and increases the maximum load accordingly. Avoiding low frequency oscillations makes subsynchronous resonance important. [13]
- Saturable reactances (or transformers) have been proposed also to reduce voltage regulation at low costs. [14]

19.7 POLE CHANGING SEIGS

Pole changing winding stator SEIGs have been proposed for isolated generator systems with variable speed operation when an up to 3(4) to 1 ratio is required. To keep the flux density in the airgap about the same for both pole numbers, the numbers of poles have to be carefully chosen.

Adequate numbers are 4/6, 6/8, 8/10, etc. The connection of phases for the two pole numbers is also important for same airgap flux density. Parallel-star and series-star for 4/6 pole combination was found adequate for the scope. [8]

The pole switching should occur near (but before) the drop-out speed for the low pole number.

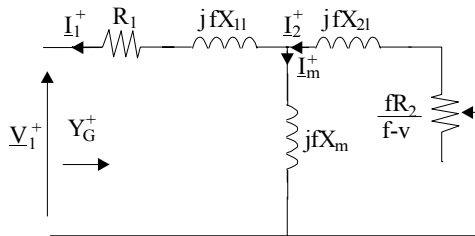
The voltage drop (for single capacitor) with load, for both numbers of poles, is about the same. Operating at lower number of poles (higher speed), the power is doubled with respect to the case of lower number of poles. Also the efficiency is higher, as expected, at higher speed.

For constant voltage, when the speed is doubled, the capacitance and VAR demands in both 6 and 4 pole configurations drop to $1/7^{\text{th}}$ and $1/3^{\text{rd}}$. When the load increases, the capacitance and VAR demands increase almost two fold. [5]

High winding factor pole changing windings with simple (two three-phase ends) pole switching power switch configurations are required (see Chapter 4). SEIGs with dual windings (of different power ratings) are also commercially available.

19.8 UNBALANCED STEADY STATE OPERATION OF SEIG

Failure of one capacitor or unbalanced load impedances in a three phase SEIG lead to unbalanced operation.



a.)

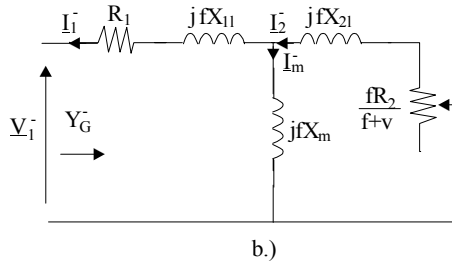


Figure 19.13 +/- sequence equivalent circuits of SEIG

A general approach to unbalanced operation is provided here by using the symmetrical component method. [15] Both the SEIG and the load may be either *delta* or *star* connected.

The equivalent circuit of IG for the positive and negative sequence, with frequency f and speed v in p.u. (as in Section 19.3 (Figure 19.7)) is shown in Figure 19.13.

For the negative sequence, the slip changes from $S^+ = f/(f-v)$ to $S^- = f/(f+v)$.

Also, as the slip frequency is different for the two sequences, $f_s^+ = S^+ \cdot f \cdot f_{1b}$; $f_s^- = S^- \cdot f \cdot f_{1b}$, the skin effect in the rotor will change R_2 in the negative sequence circuit accordingly. To a first approximation, this aspect may be neglected. The superposition of effects in the $(+, -)$ method implies that X_m is the same also, though still influenced by magnetic saturation.

Core loss is neglected for simplicity.

19.8.1 The delta-connected SEIG

Let us consider a delta connected IG tied to a delta connected admittance network Y_{ab} , Y_{ac} , Y_{bc} (Figure 19.14).

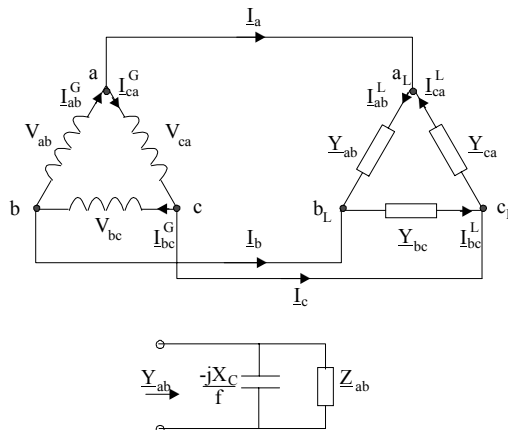


Figure 19.14 SEIG with delta connected unbalanced load and excitation capacitors

The expression of load and excitation capacitive admittance is

$$\underline{Y}_{ab} = \frac{1}{\underline{Z}_{ab}} + j \frac{f}{X_C} \quad (19.29)$$

The total load-capacitor supposedly unbalanced admittances are first decomposed into the sequence components as

$$\begin{bmatrix} \underline{Y}^0 \\ \underline{Y}^+ \\ \underline{Y}^- \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} \underline{Y}_{ab} \\ \underline{Y}_{bc} \\ \underline{Y}_{ca} \end{bmatrix} \quad (19.30)$$

The total load-capacitor phase currents $\underline{I}_{ab}^L$, $\underline{I}_{bc}^L$, $\underline{I}_{ca}^L$, can also be transformed into their sequence components as

$$\begin{bmatrix} \underline{I}_{ab}^{L0} \\ \underline{I}_{ab}^{L+} \\ \underline{I}_{ab}^{L-} \end{bmatrix} = \begin{bmatrix} \underline{Y}^0 & \underline{Y}^- & \underline{Y}^+ \\ \underline{Y}^+ & \underline{Y}^0 & \underline{Y}^- \\ \underline{Y}^- & \underline{Y}^+ & \underline{Y}^0 \end{bmatrix} \cdot \begin{bmatrix} \underline{V}_{ab}^0 \\ \underline{V}_{ab}^+ \\ \underline{V}_{ab}^- \end{bmatrix} \quad (19.31)$$

In the delta connection, there is no zero sequence voltage $\underline{V}_{ab}^0 = 0$. Consequently, the line currents $\underline{I}_a$ components $\underline{I}_a^+$ and $\underline{I}_a^-$ are

$$\begin{aligned} \underline{I}_a^+ &= \underline{I}_{ab}^{L+} - \underline{I}_{ca}^{L+} = (1-a)\underline{I}_{ab}^{L+} = (1-a) \left(\underline{Y}^0 \underline{V}_{ab}^+ + \underline{Y}^- \underline{V}_{ab}^- \right) \\ \underline{I}_a^- &= \underline{I}_{ab}^{L-} - \underline{I}_{ca}^{L-} = (1-a^2)\underline{I}_{ab}^{L-} = (1-a^2) \left(\underline{Y}^+ \underline{V}_{ab}^+ + \underline{Y}^0 \underline{V}_{ab}^- \right) \end{aligned} \quad (19.32)$$

From Figure 19.13, the generator phase current components $\underline{I}_1^+$ and $\underline{I}_1^-$ are

$$\underline{I}_1^+ = \underline{Y}_G^+ \underline{V}_1^+; \quad \underline{I}_1^- = \underline{Y}_G^- \underline{V}_1^- \quad (19.33)$$

Similar to (19.32), we may write the line current $\underline{I}_a$ components based on generator phase current components as

$$\begin{aligned} \underline{I}_a^+ &= (1-a)\underline{I}_{ab}^{G+} = -(1-a)\underline{V}_{ab}^+ \underline{Y}_G^+ \\ \underline{I}_a^- &= (1-a)\underline{I}_{ab}^{G-} = -(1-a^2)\underline{V}_{ab}^- \underline{Y}_G^- \end{aligned} \quad (19.34)$$

Note that the generator phases are balanced. Equating (19.32) to (19.34) and then dividing them leads to the elimination of $\underline{V}_{ab}^+$ and $\underline{V}_{ab}^-$ to yield

$$\left(\underline{Y}_G^+ + \underline{Y}_0 \right) \left(\underline{Y}_G^- + \underline{Y}_0 \right) - \underline{Y}^+ \underline{Y}^- = 0 \quad (19.35)$$

Equation (19.35) represents the self-excitation condition and leads to two real coefficient nonlinear equations. In general, the solution to (19.35) for a given capacitance, frequency (or speed) and load is similar to the solution for balanced condition, though a bit more involved. For balanced operation $\underline{Y}^+ = \underline{Y}^- = \underline{Y}$ and $\underline{Y}^0 = 0$. So (19.35) degenerates to $\underline{Y}_G^+ - \underline{Y} = 0$, as expected.

If the load is Y connected, it should be first transformed into an equivalent delta connection and then apply (19.35). Notice that in general the capacitors are delta connected to exploit the higher voltage available to them.

19.8.2 Star-connected SEIG

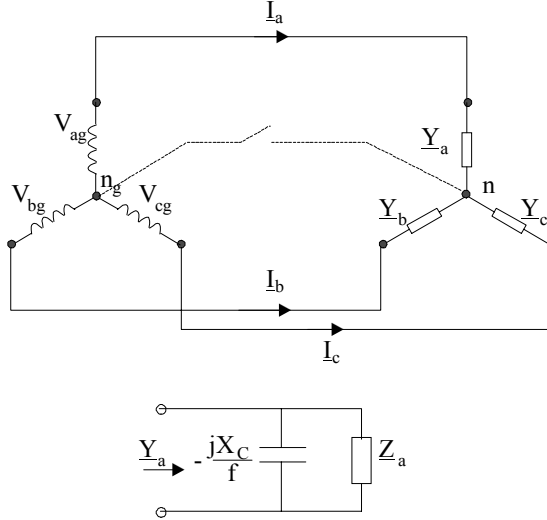


Figure 19.15 Star connected SEIG

This time the capacitors are star connected to the load. If they are delta connected, X_C for delta connection is replaced by $3X_C$ for star connection ($X_{CY} = 3X_{CA}$).

In this case, $\underline{Y}^0$, $\underline{Y}^+$ and $\underline{Y}^-$, the total capacitive load admittance components, refer to $\underline{Y}_a$, $\underline{Y}_b$, $\underline{Y}_c$.

The symmetrical components of the line current $\underline{I}_a$ calculated from the load are

$$\begin{bmatrix} \underline{I}_a^0 \\ \underline{I}_a^+ \\ \underline{I}_a^- \end{bmatrix} = \begin{bmatrix} \underline{Y}^0 & \underline{Y}^- & \underline{Y}^+ \\ \underline{Y}^+ & \underline{Y}^0 & \underline{Y}^- \\ \underline{Y}^- & \underline{Y}^+ & \underline{Y}^0 \end{bmatrix} \begin{bmatrix} \underline{V}_a^0 \\ \underline{V}_a^+ \\ \underline{V}_a^- \end{bmatrix} \quad (19.36)$$

with $\underline{I}_a^0 = 0$ (no neutral connection)

$$\underline{V}_a^0 = -\frac{(\underline{Y}^- \underline{V}_a^- + \underline{Y}^+ \underline{V}_a^+)}{\underline{Y}^0} \quad (19.37)$$

Making use of $\underline{V}_a^0$ in the star two equations of (19.36), we obtain

$$\begin{aligned} \underline{I}_a^+ &= \left(\underline{Y}^0 - \frac{\underline{Y}^+ \underline{Y}^-}{\underline{Y}^0} \right) \underline{V}_a^+ + \left(\underline{Y}^- - \frac{\underline{Y}^+ \underline{Y}^+}{\underline{Y}^0} \right) \underline{V}_a^- \\ \underline{I}_a^- &= \left(\underline{Y}^+ - \frac{\underline{Y}^- \underline{Y}^-}{\underline{Y}^0} \right) \underline{V}_a^+ + \left(\underline{Y}^0 - \frac{\underline{Y}^+ \underline{Y}^-}{\underline{Y}^0} \right) \underline{V}_a^- \end{aligned} \quad (19.38)$$

The same line current components, calculated from the generator side, are simply

$$\underline{I}_a^+ = -\underline{Y}_G^+ \underline{V}_{ag}^+; \quad \underline{I}_a^- = -\underline{Y}_G^- \underline{V}_{ag}^- \quad (19.39)$$

As the generator and the load line voltages have their sum equal to zero, even with unbalanced load, it may be shown that

$$\begin{aligned} \underline{V}_{ab}^+ &= (1-a^2) \underline{V}_a^+ = (1-a^2) \underline{V}_{ag}^+ \\ \underline{V}_{ab}^- &= (1-a) \underline{V}_a^- = (1-a) \underline{V}_{ag}^- \end{aligned} \quad (19.40)$$

Consequently, $\underline{V}_a^+ = \underline{V}_{ag}^+ \quad \text{and} \quad \underline{V}_a^- = \underline{V}_{ag}^- \quad (19.41)$

From (19.38)-(19.39), with (19.41), we obtain the self-excitation equation

$$\left(\underline{Y}_G^+ + \underline{Y}^0 - \frac{\underline{Y}^+ \underline{Y}^-}{\underline{Y}^0} \right) \left(\underline{Y}_G^- + \underline{Y}^0 - \frac{\underline{Y}^+ \underline{Y}^-}{\underline{Y}^0} \right) - \left(\underline{Y}^+ - \frac{\underline{Y}^- \underline{Y}^-}{\underline{Y}^0} \right) \left(\underline{Y}^- - \frac{\underline{Y}^+ \underline{Y}^+}{\underline{Y}^0} \right) = 0 \quad (19.42)$$

Note that if the SEIG is star-connected and the capacitor load combination is delta connected with original +0 sequence admittances as $\underline{Y}^0$, $\underline{Y}^+$, $\underline{Y}^-$, then a self-excitation equation similar to (19.35) is obtained

$$\left(\frac{1}{3} \underline{Y}_G^+ + \underline{Y}^0 \right) \left(\frac{1}{3} \underline{Y}_G^- + \underline{Y}^0 \right) - \underline{Y}^+ \underline{Y}^- = 0 \quad (19.43)$$

Also when n_g and n are connected, the zero sequence current $\underline{I}_a^0$ is not zero, generally. However there is no zero sequence generator voltage $\underline{V}_a^0 = \underline{V}_{ag}^0 = 0$.

Consequently, the situation is in this case similar to that of delta/delta connection, but the total load admittances $\underline{Y}^0$, $\underline{Y}^+$, $\underline{Y}^-$ correspond to the star connected load admittances $\underline{Y}_a$, $\underline{Y}_b$, $\underline{Y}_c$.

Whereas the above treatment is fairly standard and general, a few examples are in order.

19.8.3. Two phase open

Let us consider the case of Δ/Δ connection (Figure 19.16) with a single capacitor between a_L and b_L and a single load

$$\underline{Y}_{ab} = \underline{Y} = \frac{1}{\underline{Z}}; \quad \underline{Y}_{bc} = \underline{Y}_{ca} = 0 \quad (19.44)$$

For this case

$$\underline{Y}^0 = \underline{Y}^+ = \underline{Y}^- = \frac{\underline{Y}}{3} \quad (19.45)$$

With (19.45) the selfexcitation equation (19.35) becomes

$$3\underline{Y}_G + \underline{Y}_G^- + (\underline{Y}_G^+ + \underline{Y}_G^-)\underline{Y} = 0 \quad (19.46)$$

or

$$\frac{3}{\underline{Y}} + \frac{1}{\underline{Y}_G^+} + \frac{1}{\underline{Y}_G^-} = 0 \quad (19.47)$$

Equation (19.47) illustrates the series connection of + and-generator sequence circuits to $\frac{3}{\underline{Y}} = 3\underline{Z}$ (Figure 19.16).

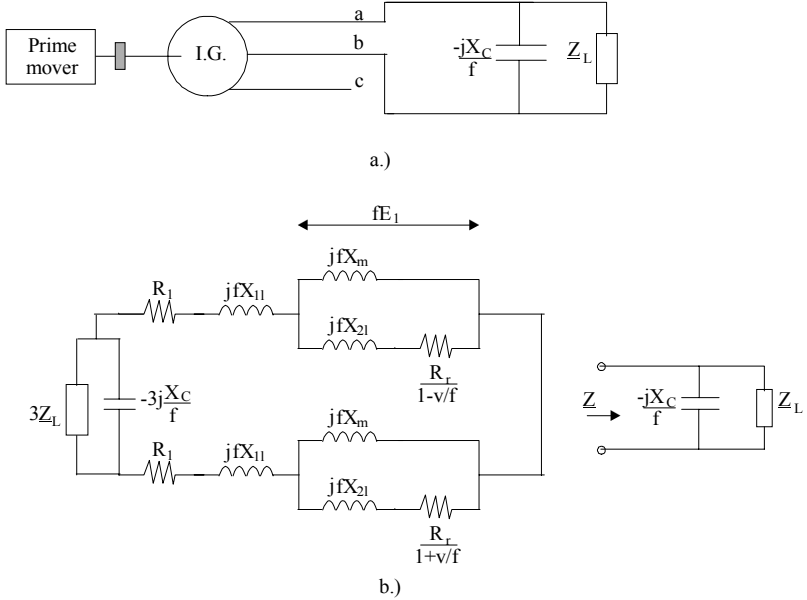


Figure 19.16 Unbalanced SEIG with Δ/Δ connection single capacitor and single load

Other unbalanced conditions may occurs. For example, if phase C opens for some reason, while the load $\underline{Z}$ is balanced, the SEIG performs as with a single capacitor and load impedance but with new load admittance $\underline{Y}_{ab} = 1.5\underline{Y}$ and $\underline{Y}_{bc} = \underline{Y}_{ca} = 0$ [15].

For a short-circuit across phase a (Δ/Δ connection) $\underline{Y}_{ab} = \infty$ and thus $\underline{Y}^0 = \underline{Y}^+ = \underline{Y}^- = \infty$. Consequently (19.35) becomes (Figure 19.16a).

$$\underline{Y}_G^+ + \underline{Y}_G^- = 0 \quad (19.48)$$

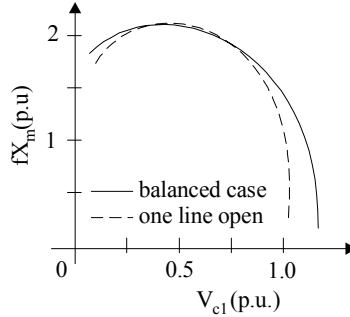


Figure 19.17 Positive sequence magnetizing characteristics

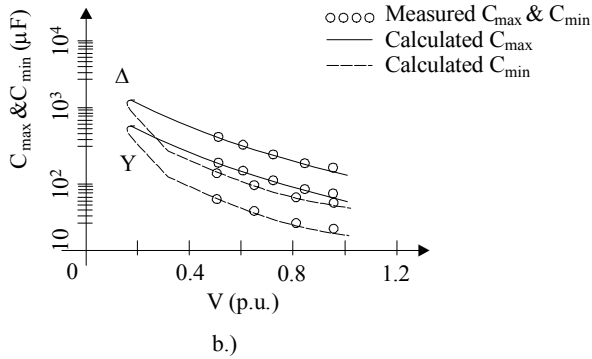
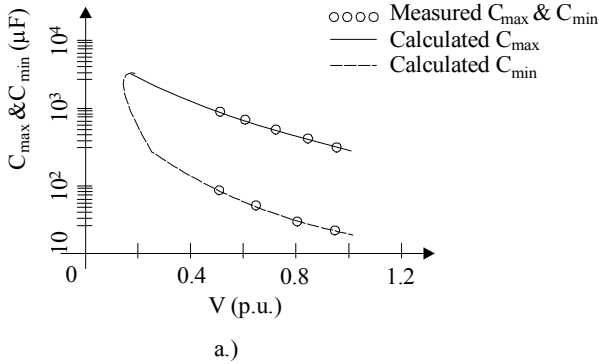


Figure 19.18 Min-max capacitors on no load
a.) balanced capacitor; b.) one capacitor only

As the capacitor is short-circuited there will be no selfexcitation. The same is true for a three phase short-circuit.

In essence, the computation of steady state performance under unbalanced conditions includes solving first the self-excitation nonlinear equations (19.35) or (19.42) or (19.43), (19.47) for given speed (frequency), load and capacitance, to find the frequency (speed) and the magnetization reactance X_m . Then, as for the balanced conditions, equivalent circuits are solved, provided the magnetization curve $E_1(X_m)$ is known. It was proved in Reference [15] that the positive sequence magnetization curves obtained for balanced no load and one-line-open load differ from each other in the saturation zone (Figure 19.17).

It turns out that, whenever a zero line current occurs, the one-line-open characteristic in Figure 19.17 should be applied. [15]

Sometimes the range of self-excitation capacitance is needed. Specifying the maximum magnetization reactance X_{max} , the speed (frequency), machine parameters and load, the solution of self-excitation equations developed in this paragraph produces the required frequency (speed) and capacitances.

There are two solutions for the capacitances, C_{max} and C_{min} , and they depend strongly on load and speed. For maximum load, the two values become equal to each other. Beyond that point the voltage collapses.

Sample results obtained for C_{max} and C_{min} on no load under balanced and unbalanced (one capacitor only) conditions are shown in Figure 19.18 [15] for $r_1 = 0.09175$, $r_2 = 0.06354$, $p_1 = 2$, $f_{1b} = 60\text{Hz}$, $x_{1l} = x_{2l} = 0.2112$, $x_{max} = 2.0$.

Meticulous investigation of various load and capacitor unbalances on load has proved [15] that the theory of symmetrical components works well.

The range of C_{min} to C_{max} for delta connection is 3 times smaller for the star connection, In terms of parameter-sensitivity analysis, the trends for unbalanced load are similar to those for balanced load. However, the efficiency is notably reduced and stays low with load variation.

19.9 TRANSIENT OPERATION OF SEIG

SEIGs work alone or in parallel on variable loads. Load and speed perturbations, voltage build-up on no load, excitation capacitance changes during load operation are all causes for transients. To investigate the transients the d-q model is generally preferred. Also stator coordinates are used to deal easily with eventual parallel operation or active loads (a.c. motors).

The d-q model (in stator coordinates) for the SEIG alone, including cross-coupling saturation [16, 17], is given below

$$[V_G] = -[R_G][i_G] - [L_G]p[i_G] - \omega_{rG}[G_G][i_G] \quad (19.49)$$

$$\text{with} \quad [V_G] = [V_d, V_q, 0, 0] \quad (19.50)$$

$$[i_G] = [i_d, i_q, i_{dr}, i_{qr}] \quad (19.51)$$

The torque

$$T_{eG} = \frac{3}{2} p_{lG} L_m (\dot{i}_q \dot{i}_{dr} - \dot{i}_d \dot{i}_{qr}) \quad (19.52)$$

$$\frac{J}{p_{lG}} \frac{d\omega_{rG}}{dt} = T_{PM} - T_{eG} \quad (19.53)$$

$$pV_d = \frac{1}{C} \dot{i}_{dc}; \quad pV_q = \frac{1}{C} \dot{i}_{qc} \quad (19.54)$$

$$\dot{i}_{dc} = \dot{i}_d + \dot{i}_{dL}; \quad \dot{i}_{qc} = \dot{i}_q + \dot{i}_{qL} \quad (19.55)$$

$\dot{i}_{dc}$, $\dot{i}_{qc}$, $\dot{i}_{dL}$, $\dot{i}_{qL}$ are d, q components of capacitor and load currents, respectively.

The association of signs in (19.49) corresponds to generator mode.

Now the parameter matrices R_G , L_G , G_G are

$$R_G = \text{Diag}[R_1, R_1, R_2, R_2]$$

$$L_G = \begin{bmatrix} L_{ld} & L_{dq} & L_{md} & L_{dq} \\ L_{dq} & L_{lq} & L_{dq} & L_{mq} \\ L_{md} & L_{dq} & L_{2d} & L_{dq} \\ L_{dq} & L_{mq} & L_{dq} & L_{2q} \end{bmatrix} \quad (19.56)$$

$$G_G = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & L_m & 0 & L_2 \\ -L_m & 0 & -L_2 & 0 \end{bmatrix} \quad (19.57)$$

L_m is the magnetisation inductance and i_m the magnetisation current

$$\dot{i}_{md} = \dot{i}_d + \dot{i}_{dr}; \quad \dot{i}_{mq} = \dot{i}_q + \dot{i}_{qr}; \quad \dot{i}_m = \sqrt{\dot{i}_{md}^2 + \dot{i}_{mq}^2} \quad (19.58)$$

The crosscoupling transient inductance L_{dq} [16,17] is

$$L_{dq} = \frac{\dot{i}_{md} \dot{i}_{mq}}{\dot{i}_m} \frac{dL_m}{di_m} \quad (19.59)$$

Also the transient magnetisation inductances along the two axes L_{md} and L_{mq} [16, 17] are

$$L_{md} = L_m + \frac{\dot{i}_{md}^2}{\dot{i}_m} \frac{dL_m}{di_m} \quad (19.60)$$

$$L_{mq} = L_m + \frac{i_{mq}^2}{i_m} \frac{dL_m}{di_m} \quad (19.61)$$

Also

$$\begin{aligned} L_{1d} &= L_{1l} + L_{md}; & L_{1q} &= L_{1l} + L_{mq} \\ L_{2d} &= L_{2l} + L_{md}; & L_{2q} &= L_{2l} + L_{mq} \end{aligned} \quad (19.62)$$

The load equations are to be added. The load may be passive or active. A series $R_L L_L C_L$ load would have the equations

$$\begin{aligned} [V_G] &= [R_L][i_{sL}] + [L_L] \frac{d[i_{sL}]}{dt} + [V_{cL}] \\ \frac{d[V_{cL}]}{dt} &= \frac{1}{C_L} [i_{sL}]^T, \quad [V_{cL}] = [V_{cd} \ V_{cq}]^T \\ [i_{sL}] &= [i_{dL} \ i_{qL}]^T \end{aligned} \quad (19.63)$$

In contrast, an induction motor load (in stator coordinates) is characterized by a set of equations such as

$$\begin{aligned} [V_G] &= [R_M][i_M] + [L_M] \frac{d[i_M]}{dt} + \omega_{rM} [G_M][i_M] \\ \frac{J_M}{P_{1M}} \frac{d\omega_{rM}}{dt} &= T_{eM} - T_{Load} \\ T_{eM} &= \frac{3}{2} P_{1M} L_{mM} (i_{qM} i_{drM} - i_{dM} i_{qrM}) \\ [i_M] &= [i_{dM} \ i_{qM} \ i_{drM} \ i_{qrM}]^T \end{aligned} \quad (19.64)$$

Motor equations are similar to generator equations, as are the parameter definitions in (19.56)-(19.62).

We also should note that $i_{dM} = i_{dL}$, $i_{qM} = i_{qL}$. When multiple passive and active loads are connected to the generator, the generator current $[i_L] = [i_{dL}, i_{qL}]$.

Solving for the transients in the general case is done through numerical methods. The unknowns are the various currents and the capacitor voltages. The capacitor currents are dummy variables.

19.10 SEIG TRANSIENTS WITH INDUCTION MOTOR LOAD

There are practical situations, in remote areas, when the SEIG is supplying an induction motor which in turns drives a pump or similar load.

A pump load is characterized by increasing torque with speed such that

$$T_{load} \approx T_{L0} + K_L \omega_{rM}^2 \quad (19.65)$$

The most severe design problem of such a system is the starting (transient) process. The rather low impedance of IM at low speeds translates into high transient currents from the SEIG. On the other hand, a large excitation capacitor is needed for rated voltage with the motor on load. When the motor is turned off, this large capacitor produces large voltage transients. Part of it must be disconnected or an automatic capacitance reduction to control the voltage is required. An obvious way out of this difficulty would be to have a smaller (basic) capacitance (C_G) connected to the generator and one (C_M) to the motor (Figure 19.19).

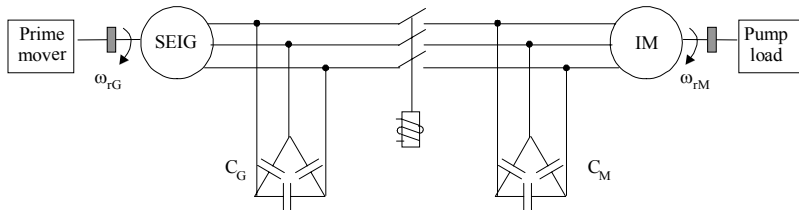


Figure 19.19 SEIG with IM load and splitted excitation capacitor

First, the SEIG is accelerated by the prime mover until it establishes a certain speed with a certain output voltage. Then the IM is connected. Under rather notable voltage and current transients, the motor accelerates and settles at a speed corresponding to the case when the motor torque equals the pump torque.

To provide safe starting, the generator rated power should be notably in excess of the motor rated power. In general, even an 1/0.6 ratio marginally suffices.

Typical such transients for a 3.7kW SEIG and a 2.2kW motor with $C_G = 18\mu\text{F}$, $C_M = 16\mu\text{F}$, are shown in Figure 19.20 [18].

Voltage and current transients are evident, but the motor accelerates and settles on no load smoothly. Starting on pump load is similar but slightly slower.

On the other hand, the voltage build-up in the SEIG takes about 1-2 seconds. Sudden load changes are handled safely up to a certain level which depends on the ratio of power rating of the motor of the SEIG.

For the present case, a zero to 40% motor step load is handled safely but an additional 60% step load is not sustainable. [18] Very low overloading is acceptable unless the SEIG to motor rating is larger than $3 \div 4$.

In case of overloading, an over current relay set at 1.2-1.3p.u. for 300-400ms can be used to trip the circuit.

During a short-circuit at generator terminals, surges of 2 p.u. in voltage and 5 p.u. in current occur for a short time (up to 20 ms) before the voltage collapses.

Though the split capacitor method (Figure 19.19) is very practical, for motors rated less than 20% of SEIG rating, a single capacitor will do.

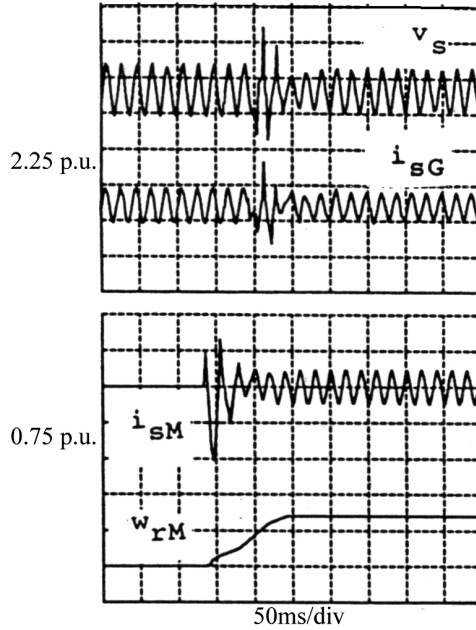


Figure 19.20 Motor load starting transients for a SEIG, $C_G = 18\mu\text{F}$, $C_m = 16\mu\text{F}$

19.11 PARALLEL OPERATION OF SEIGS

An isolated power system made of a few SEIGs is a practical solution for upgrading the generating power rating upon demand. Such a stand alone power system may have a single excitation capacitor but most probably, it has to be variable to match the load variations which inevitably occur. Capacitor change may be done in steps through a few power switches or continuously through power electronics control of a paralleled inductor current (Figure 19.21).

The operation of such a power grid on steady state is to be approached as done for the single SEIG. However, the magnetization curves and parameters of all SEIGs are required. Finally, the self-excitation condition will be under the form of an admittance summation equal to zero. Neglecting the “de-excitation” inductance L_{ex} , the terminal voltage equation is

$$\mathbf{V}_s \left(\frac{1}{R_L} - \frac{j}{fX_L} + \frac{jf}{X_C} \right) = \sum_{i=1}^N \mathbf{I}_{si} \quad (19.66)$$

The SEIG's equations (section 19.3 and Figure 19.7) may be expressed as

$$\underline{I}_{mi} + \underline{I}_{si} = \underline{I}_{2i} = \frac{-f \underline{E}_{1i}}{\frac{R_{2i}}{1 - \frac{v_i}{f}} + jfX_{2i}} \quad (19.67)$$

v_i is the p.u. speed of the i^{th} generator. $X_{mi}(E_{1i})$ represents the magnetization curve of the i^{th} machine. All these curves have to be known. Again for a given excitation capacitance C , motor parameters and speeds of various SEIGs and load, the voltage, frequency, SEIG currents, capacitor currents and load currents and load powers (active and reactive) could be iteratively determined from (19.66)-(19.67). A starting value of f is in general adopted to initiate the iterative computation. For sample results, see [19].

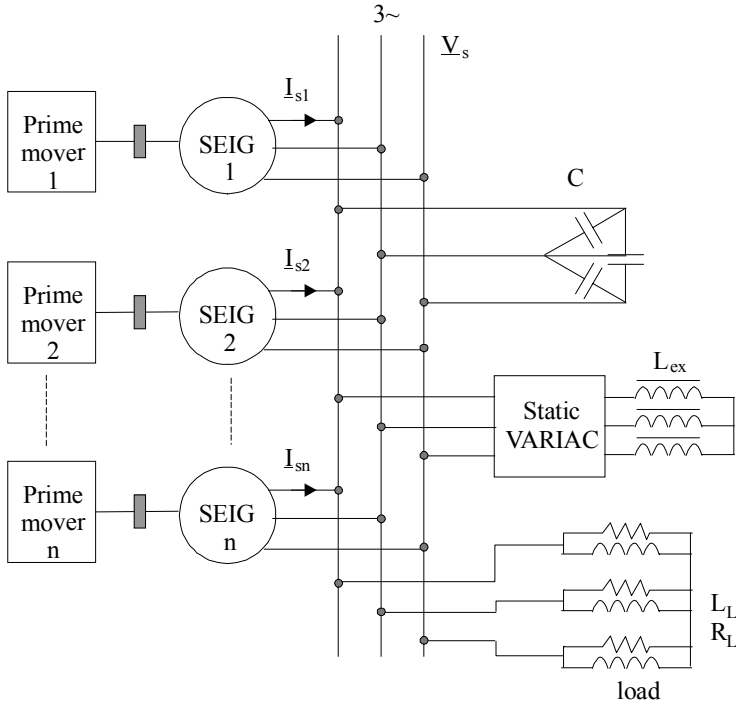


Figure 19.21 Isolated power grid with paralleled SEIGs

The SEIGs speeds in p.u. have to be close to each other to avoid that some of them switch to motoring mode. Transient operation may be approached by using the d-q models of all SEIGs with the summation of the stator phase currents equal to the capacitor plus load current. So the solution of transients is similar to that for a single SEIG, as presented earlier in this chapter, but the number of equations is larger. Only numerical methods such as Runge-Kutta, Gear, etc. may succeed in solving such stiff nonlinear systems.

19.12 THE DOUBLY-FED IG CONNECTED TO THE GRID

As shown in [Figure 19.1](#), a wound-rotor induction generator (dubbed as doubly - fed) may deliver power not only through the stator but also through the rotor; provided a bi-directional power flow converter is used in the rotor circuit. The main merit of the doubly-fed IG is its capability to deliver constant voltage and frequency output for $\pm(20-40)\%$ speed variation around conventional synchronous speed. If the speed variation range is $(20-40)\%$ so is the rating of static power converter and transformer in the rotor circuit ([Figure 19.1](#)). For bi-directional power flow in the rotor circuit, single stage converters (cycloconverters or matrix converters) or dual-stage back-to-back voltage source PWM inverters have to be used.

Independent reactive and active power flow control-with harmonics elimination-may be achieved this way for both super and subsynchronous speed operation. Less costly solutions use a unidirectional power flow converter in the rotor when only super or subsynchronous operation as generator is possible.

Here we are interested mainly in the IG behaviour when doubly fed. So we will consider sinusoidal variables with rotor voltage amplitude, frequency and phase open to free change through an ideal bi-directional power electronics converter.

19.12.1. Basic equations

To investigate the doubly-fed IG (DFIG) the d-q (space - phasor) model as presented in Chapter 13 on transients is used.

In synchronous coordinates

$$\begin{aligned}\bar{V}_1 &= (R_1 + (p + j\omega_1)L_1)\bar{i}_1 + (p + j\omega_1)L_m\bar{i}_2 \\ \bar{V}_2 &= (p + jS\omega_1)L_m\bar{i}_1 + (R_2 + (p + jS\omega_1)L_2)\bar{i}_2\end{aligned}\quad (19.68)$$

$$\bar{V}_1 = V_d + jV_q; \quad \bar{V}_2 = V_{dr} + jV_{qr}$$

$$\bar{i}_1 = i_d + ji_q; \quad \bar{i}_2 = i_{dr} + ji_{qr}$$

with

$$L_1 = L_{11} + L_m; \quad L_2 = L_{21} + L_m$$

$$T_e = \frac{3}{2} p_1 L_m \operatorname{Imag}[\bar{i}_1 \bar{i}_2^*] \quad \frac{Jp\omega_r}{p_1} = T_{PM} - T_e$$

We should add the Park transformation

$$\begin{vmatrix} V_d \\ V_q \end{vmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_{1,2} & \cos\left(-\theta_{1,2} + \frac{2\pi}{3}\right) & \cos\left(-\theta_{1,2} - \frac{2\pi}{3}\right) \\ \sin(-\theta_{1,2}) & \sin\left(-\theta_{1,2} + \frac{2\pi}{3}\right) & \sin\left(-\theta_{1,2} - \frac{2\pi}{3}\right) \end{bmatrix} \begin{vmatrix} V_a \\ V_b \\ V_c \end{vmatrix} \quad (19.69)$$

The transformation is valid for stator and rotor

$$\theta_1 = \int \omega_1 dt = \omega_1 t \quad \text{- for constant frequency stator;}$$

$$\theta_2 = \int (\omega_1 - \omega_r) dt = \theta_1 - \int \omega_r dt \quad \text{- for the rotor with variable speed;}$$

So,

$$\frac{d\theta_2}{dt} = \omega_1 - \omega_r = S\omega_1 \quad (19.70)$$

For constant speed ($\omega_r = \text{constant}$)

$$\theta_2 = S\omega_1 t + \delta \quad (19.71)$$

Also, for an infinite power bus

$$V_{1abc} = V_1 \sqrt{2} \cos \left(\omega_1 t - (i-1) \frac{2\pi}{3} \right)$$

$$V_{2abc} = V_2 \sqrt{2} \cos \left(\omega_1 t - \delta - (i-1) \frac{2\pi}{3} \right) \quad (19.72)$$

In (19.72) the rotor phase voltages V_{2abc} are expressed in stator coordinates. This explains the same frequency in V_{1abc} and V_{2abc} ($\theta_1 = 0$, $\theta_2 = -\omega_r t$). Using (19.72) and (19.71) in (19.69) we obtain

$$V_{1d} = \sqrt{2} V_1; \quad V_{1q} = 0 \quad (19.73)$$

For constant speed

$$V_{2d} = \sqrt{2} V_2 \cos \delta; \quad V_{2q} = -\sqrt{2} V_2 \sin \delta$$

As seen from (19.73), in synchronous coordinates, the DFIG voltages in the stator are dc quantities. Under steady state-constant δ -the rotor voltages are also d.c. quantities, as expected. The angle δ may be considered as the power angle and thus DFIG operates as a synchronous machine. The rotor voltage $\sqrt{2} V_2$ and its phase δ with respect to stator voltage in same coordinates (synchronous in our case) and slip S are thus the key factors which determine the machine operation mode (motor or generator) and performance.

The proper relationship between V_2 , δ for various speeds (slips) represents the fundamental question for DFIG operation.

The various phase displacements in (19.71)-(19.72) are shown in [Figure 19.22](#).

The d-q model equations serve to solve most transients in the time domain by numerical methods with $\bar{V}_1$, $\bar{V}_2$ and prime mover torque T_{PM} as inputs and the various currents and speed as variables.

However to get an insight into the DFIG behaviour we here investigate steady state operation and its stability limits.

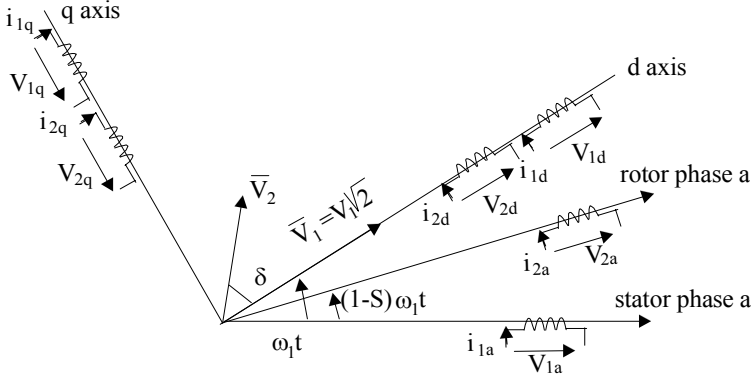


Figure 19.22 The d-q axis model and the voltage vectors $\bar{V}_1$, $\bar{V}_2$ in synchronous coordinates

19.12.2 Steady state operation

The steady state performance may be calculated with $S = S_0$ and $\delta = \delta_0$ and $\bar{V}_1$, $\bar{V}_2$ from (19.73)

$$\begin{aligned} \bar{V}_1 \sqrt{2} &= R_1 I_{d0} - \omega_1 \psi_{q0}; \quad \psi_{q0} = L_m I_{qr0} - L_1 I_{q0} \\ 0 &= R_1 I_{q0} + \omega_1 \psi_{d0}; \quad \psi_{d0} = L_m I_{dr0} + L_1 I_{d0} \\ V_2 \sqrt{2} \cos \delta &= R_2 I_{dr0} - S_0 \omega_1 \psi_{qr0}; \quad \psi_{qr0} = L_2 I_{qr0} + L_m I_{q0} \\ -V_2 \sqrt{2} \sin \delta &= R_2 I_{qr0} + S_0 \omega_1 \psi_{dr0}; \quad \psi_{dr0} = L_2 I_{dr0} + L_m I_{d0} \end{aligned} \quad (19.74)$$

with the torque T_{e0} given by

$$T_{e0} = \frac{3}{2} p_1 L_m (I_{q0} I_{dr0} - I_{d0} I_{qr0}) \quad (19.75)$$

The main characteristic is $T_{e0}(\delta)$ for the rotor voltage amplitude V_2 as a parameter. The frequency of rotor voltage system is in the real machine $S\omega_1$, while its phase shift with respect to the stator voltages at time zero is δ .

Though an analytical solution at $T_{e0}(\delta)$ is obtainable from (19.74)-(19.75) as they are, for $R_1 = R_2 = 0$ a much simpler solution is obtained. Such a solution is acceptable for large power and slip values

$$(T_{e0})_{\substack{R_1=R_2=0 \\ S_0 \neq 0}} = 3P_1 \left(\frac{V_1}{\omega_1} \right) \left(\frac{V_2}{S\omega_1} \right) \frac{\sin \delta}{\omega_1 L_{sc}} \left(\frac{L_m}{L_1} \right); \quad L_{sc} = (L_1 L_2 - L_m^2) L_1 \quad (19.76)$$

Positive torque means motoring. Positive δ means V_2 lagging $\bar{V}_1$. It is now evident that the behavior of DFIG resembles that of a synchronous machine. As long as the ratio $V_2/S_0\omega_1$ is constant, the maximum torque value remains the

same. But this is to say that when the rotor flux is constant, the maximum torque is the same and thus the stability boundaries remain large.

As $R_1 = R_2 = 0$ assumption does not work at zero slip ($S_0 = 0$), we may derive this case separately from (19.74) with $R_1 = 0$, $R_2 \neq 0$, but with $S_0 = 0$. Hence,

$$(T_{e0})_{R_1=0}^{S_0=0} = 3 \left(\frac{p_1}{\omega_1} \right) \left(\frac{V_1 V_2}{R_2} \right) \left(\frac{L_m}{L_1} \right) \cos \delta \quad (19.77)$$

The two approximations of the torque, one valid at rather large slips and the other valid at zero slip (conventional synchronism) are shown in [Figure 19.23](#).

The statically stable operation zones occur between points A_M and A_G .

For $S_0 \neq 0$ motor and generator operation is in principle feasible both for super and subsynchronous speeds ($S_0 < 0$ and $S_0 > 0$). However, the complete expression of torque for $S_0 \neq 0$, which includes the resistances, will alter the simple expression of torque shown in (19.76). A better approximation would be obtained for $R_2 \neq 0$ with $R_1 = 0$. For low values of slip S_0 the rotor resistance is important even for large power induction machines.

After some manipulations (19.74) and (19.75) yield

$$(T_{e0})_{R_1=0} = 3 \left(\frac{p_1 V_1 V_2}{\omega_1} \right) \left(\frac{L_m}{L_1} \right) \frac{R_2 \cos \delta + S_0 \omega_1 L_{sc} \sin \delta - \frac{V_1}{V_2} R_2 S_0 \frac{L_m}{L_1}}{(R_2^2 + (S_0 \omega_1 L_{sc})^2)} \quad (19.78)$$

As expected, when $R_2 = 0$ expression (19.76) is reobtained and when $S_0 = 0$, expression (19.77) follows from (19.78).

Expression (19.78) does not collapse either for $V_2 = 0$ or for $S_0 = 0$. It only neglects the stator resistances, for simplicity ([Figure 19.24](#)).

For $\delta_0 = 0$ the torque is

$$(T_{e0})_{R_1=0}^{\delta_0=0} = \frac{3p_1 V_1 V_2}{\omega_1} \frac{\left(\frac{L_m}{L_1} - S_0 \frac{V_1}{V_2} \right)}{R_2^2 + (S_0 \omega_1 L_{sc})^2} \quad (19.79)$$

So $(T_{e0})_{\delta_0=0}$ may be either positive or negative

$$\frac{V_2}{V_1} > \frac{L_1 S_0}{L_m}; \quad (T_{e0})_{\delta_0=0} > 0 \quad (19.80)$$

For S_0 negative the situation in (19.80) is reversed. As seen from [Figure 19.24](#) the stability zones of motoring and generating modes are no longer equally large due to rotor resistance R_2 and also due to the ratio V_2/V_1 and the sign of slip $S_0 > 0$.

The extension of the stability zone A_G - A_M in terms of δ_{KG} to δ_{0KM} may be simply found by solving the equation

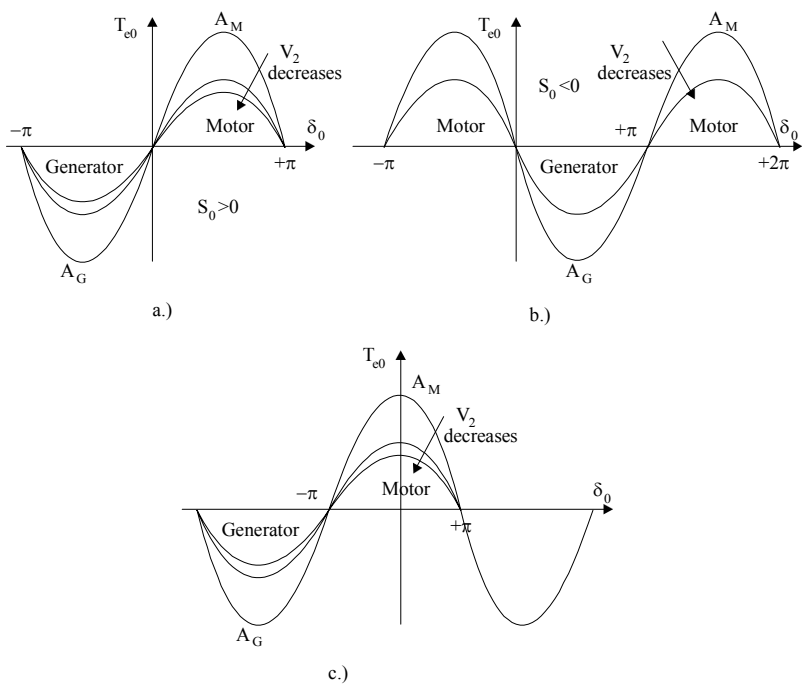


Figure 19.23 Ideal torque-angle curves
a.) & b.) at non zero (rather large) slips $|S| > 0.1$ - $R_1 = R_2 = 0$ and c.) at zero slip ($R_1 = 0, R_2 \neq 0$)

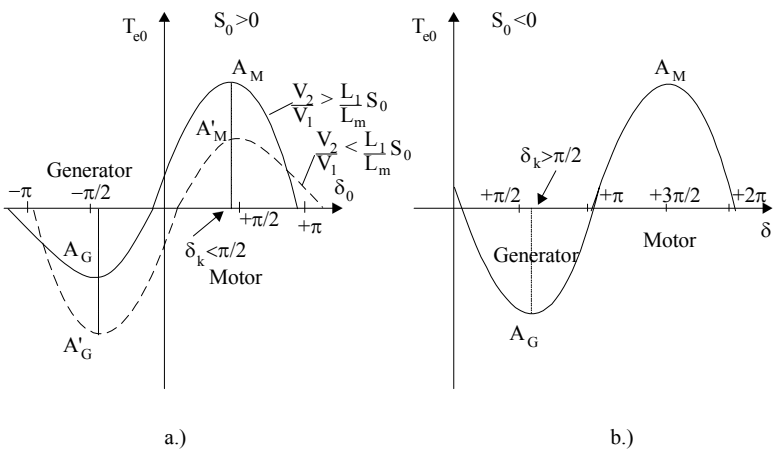


Figure 19.24 Realistic torque-angle curves ($R_2 \neq 0, R_1 = 0$)
a.) $S_0 > 0$; b.) $S_0 < 0$

$$\frac{\partial T_{e0}}{\partial \delta_0} = 0; \quad -R_2 \sin \delta_K + S_0 \omega_1 L_{sc} \cos \delta_K = 0 \quad (19.81)$$

$$\tan \delta_{K,G,M} = \frac{S_0 \omega_1 L_{sc}}{R_2} \quad (19.82)$$

The lower the value of the rotor resistance, the larger the value of $\delta_{K,G,M}$ and thus the larger the total stability angle zone travel ($A_G - A_M$).

Slightly larger stability zones for generating occur for negative slips ($S_0 < 0$). As the slip decreases the band of the stability zones decreases also (see 19.82).

The static stability problem may be approached through the eigenvalues method [20] of the linearized system only to obtain similar results even with nonzero stator resistance.

The complete performance of DFIG may be calculated by directly solving the system (19.74) for currents. Saturation may be accounted for by noting that $L_1 = L_{11} + L_m$, $L_2 = L_{21} + L_m$ and $L_m(i_m)$ -magnetization curve-is given, with

$$i_m = \sqrt{i_{dm}^2 + i_{qm}^2}; \quad i_{dm} = i_d + i_{dr}; \quad i_{qm} = i_q + i_{qr}$$

The core losses may be added also, both in the stator and rotor as slip frequency is not necessarily small.

The stator and rotor power equations are

$$\underline{S}_1 = \frac{3}{2} (V_d i_{d0} + V_q i_{q0}) + j \frac{3}{2} (V_d i_{q0} - V_q i_{d0}) \quad (19.83)$$

$$\underline{S}_2 = \frac{3}{2} (V_{dr} i_{dr0} + V_{qr} i_{qr0}) + j \frac{3}{2} (V_{dr} i_{qr0} - V_{qr} i_{dr0}) \quad (19.84)$$

In principle, the active and reactive power in the stator or rotor may be positive or negative depending on the capabilities with respect of the power electronics converter connected in the rotor circuit.

Advanced vector control methods with decoupled active and reactive power control of DFIG has been recently proposed. [21, Chapter 14]

Slip recovery systems, which use unidirectional power flow power electronics converters in the rotor, lead to limited performance in terms of power factor, harmonics and flexibility. Also, they tend to have equivalent characteristics different from those discussed here. They are well documented in the literature. [22] Special doubly-fed IMs-with dual stator windings (p_1 and p_2 pole pairs) and nested cage rotor with $p_1 + p_2$ poles-have been recently proposed [23]. Also dual stator windings with p_1 and p_2 pole pairs and a regular cage-rotor may be practical. The lower power winding is inverter fed. With the wind energy systems on the rise and low power hydropower plants gaining

popularity, the IG systems with variable speed are expected to have a dynamic future.

19.13 SUMMARY

- Three phase induction machines are used as generators both in wound rotor (doubly - fed) or the cage-rotor configurations.
- IGs may work in isolation or grid-connected.
- IGs may be used in constant or variable speed, constant or variable frequency, and constant or variable output voltage systems.
- As a rule less frequency sensitive isolated systems use cage rotor IGs with self-excitation (SEIG).
- Grid connected systems use both cage-rotor IGs (CRIGs) or doubly fed (wound rotor) IGs (DFIGs).
- Selfexcited IGs (SEIGs) use parallel capacitors at the terminals. For a given speed, IG, and a given no load voltage, there is a specific value of the capacitor that can produce it. Magnetic saturation is a must in SEIGs.
- When SEIGs with constant speed prime mover are loaded the frequency and voltage decrease with load. The slip (negative) increases with load.
- The basic problem for steady state operation starts with a given frequency, load, IG parameters and selfexcitation capacitance to find the speed (slip), voltage, currents, power, efficiency, etc.
- Impedance and admittance methods are used to study steady state. While the impedance methods lead to 4(5)th order equations in S (or X_m), an admittance method that leads to a second order equation in slip is presented. This greatly simplifies the computational process as X_m (the magnetisation reactance) is obtained from a first order equation.
- There is a minimum load resistance which still allows SEIG selfexcitation which is inversely proportional to the selfexcitation capacitance C (19.22).
- The ideal maximum power slip is $S_{max} = -R_2/(fX_{2l})$, with R_2 , X_{2l} as rotor resistance and leakage reactance at rated frequency and f , stator frequency in p.u. This expression is typical for constant airgap flux conditions in vector controlled IM drives.
- The SEIG steady state curves are voltage/current, voltage/power, frequency/ power for given speed and selfexcitation capacitance.
- SEIG parameter sensitivity studies show that voltage and maximum output power increases with capacitance.
- For no load the minimum capacitor that can provide selfexcitation is inversely proportional to speed squared.
- When feeding an IM from a SEIG, in general the rating of SEIG should be 2-3 times the motor rating though for pump-load starting even 1.6 times overrating will do. To avoid high overvoltages when the IM load is disconnected the excitation capacitor may be split between the IM and the SEIG.

- Pole changing stator SEIGs are used for wide speed range harnessing of SEIG's prime mover energy more completely (wind turbines for example).
- Pole changing winding design has to maintain large enough airgap flux densities, that saturate the cores to secure selfexcitation over the entire design speed range.
- Unbalanced operation of SEIGs may be analysed through the method of symmetrical components and is basically similar to that of balanced load but efficiency is notably lower and the phase voltages may differ from each other notably. When one line current is zero the single capacitor no load curve should be considered.
- Transients of SEIG occur for voltage build up or load perturbation. They may be investigated by the d-q model. At shortcircuit, for example, with IM-load, the SEIG experiences for a few periods 2 p.u. voltage and up to 5 p.u. current transients before the voltage collapses.
- Parallel operation of SEIGs in isolated systems makes use of a single but variable capacitor to control the voltage for variable load.
- The slip of all SEIGs in parallel has to be negative to avoid motoring. So the speeds (in p.u.) have to be very close to each other.
- Full usage of doubly fed induction generators (DFIG) occurs when it allows bidirectional power flow in the rotor circuit.
Generating is thus feasible both sub and over conventional synchronous speed. Separate active and reactive power control may be commanded.
- The study of DFIG requires the d-q model which allows for an elegant treatment of steady state with rotor voltage V_2 and power angle δ as variables and slip S_0 as parameter. The DFIG works as a synchronous machine with constant stator voltage V_1 and frequency. The rotor voltage a.c. system has the slip frequency. Thus variable speed is handled implicitly.
- The stability angle δ_K extension increases with slip and leakage reactance and decreases with rotor resistance. Also V_2/V_1 (voltage ratio) plays a crucial role in stability. Constant $(V_2/S\omega_1)$ ratio-constant rotor flux-tends to hold the peak torque less variable with slip and thus enhances stability margins.
- Eigen values of the linearized d-q model may serve well to investigate the DFIG stability boundaries. Vector control with separate active and reactive rotor power control change the behaviour of the DFIG for the better in terms of both steady state and transients [21, Chapter 14].
- New topologies such as dual pole stator winding (p_1, p_2 pole pairs) with $p_1 + p_2$ rotor cage nests [23] and, respectively, conventional cage rotors [24] have been recently proposed. The IG subject seems far from exhausted.

19.14 REFERENCES

1. P. K. S. Khan, J. K. Chatterjee, Three-Phase Induction Generators, A Discussion on Performance, EMPS, vol. 27, no. 8, 1999, pp. 813-832.
2. E. D. Basset, F. M. Potter, Capacitive Excitation of Induction Generators, Electrical Engineering, vol. 54, 1935, pp. 540-545.
3. S. S. Murthy, O. P. Malik, A. K. Tandon, Analysis of Self-excited Induction Generators, Proc IEE, vol. 129C, no. 6, 1982, pp. 260-265.
4. L. Shridhar, B. Singh, C. S. Jha, A Step Toward Improvements in the Characteristics of Self-excited Induction Generators, IEEE Trans. vol. EC-vol. 8, 1993, pp. 1, pp. 40-46.
5. S. P. Singh, B. Singh, B. P. Jain, Steady State Analysis of Self-excited Pole-Changing Induction Generator, The Inst. of Engineering (India), Journal-EL, vol. 73, 1992, pp. 137-144.
6. S. P. Singh, B. Singh, M. P. Jain, A New Technique for the Analysis of Self-excited Induction Generator, EMPS, vol. 23, no. 6, 1995, pp. 647-656.
7. L. Quazene, G. McPherson Jr, Analysis of Isolated Induction Generators, IEEE Trans. vol. PAS-102, no. 8, 1983, pp. 2793-2798.
8. N. Ammasaigounden, M. Subbiah, M. R. Krishnamurthy, Wind Driven Self-Excited Pole-Changing Induction Generators, Proc. IEE, vol. 133B, no. 5., 1986, pp. 315-321.
9. K. S. Sandhu, S. K. Jain, Operational Aspects of Self-excited Induction Generator Using a New Model, EMPS vol. 27, no. 2, 1999, pp. 169-180.
10. I. Boldea, S. A. Nasar, Vector control of a.c. drives, book, CRC Press, 1992, Boca Raton, Florida.
11. N. N. Malik, A. A. Mazi, Capacitance Requirements for Isolated Self-Excited Induction Generators, IEEE Trans, vol. EC-2, no. 1, 1987, pp. 62-68.
12. A. Kh. Al-Jabri, A. I. Alolah, Limits On the Performance of the Three-Phase Self-Excited Induction Generators, IEEE Trans, vol. EC-5, no. 2, 1990, pp. 350-356.
13. E. Bim, J. Szajner, Y. Burian, Voltage Compensation of an Induction Generator with Long Shunt Connection, IBID vol. 4, no.3, 1989, pp. 506-513.
14. S. M. Alghumainen, "Steady state analysis of an induction generator self-excited by a capacitor in parallel with a saturable reactor", EMPS vol.26, no.6, 1998, pp.617-625.

15. A. H. Al-Bahrani, Analysis of Self-Excited Induction Generators Under Unbalanced Conditions, EMPS, vol. 24, no. 2, 1996, pp.117-129.
16. I. Boldea, S. A. Nasar, Unified Treatment of Core Losses and Saturation in The Orthogonal-Axis Model of Electric Machines, Proc. IEE-vol. 134B, no. 6, 1987, pp. 355-363.
17. K. E. Hallenius, P. Vas, J. E. Brown, The Analysis of Saturated Self-excited Asynchronous Generator, IEEE Trans., vol. EC-6, no. 2, 1991, pp. 336-345.
18. B. Singh, L. Shridhar, C. B. Iha, Transient Analysis of Self-excited Induction Generator Supplying Dynamic Load, EMPS vol. 27, no. 9, 1999, pp. 941-954.
19. Ch. Chakraborty, S. N. Bhadra, A. K. Chattopadhyay, Analysis of Parallel-Operated Self-Excited Induction Generators, IEEE Trans. vol EC-14, no. 2, 1999, pp. 209-216.
20. A. Masmoudi, A. Tuomi, M. B. A. Kamoun, M. Poloujadoff, Power Flow Analysis and Efficiency Optimisation of a Double Fed Synchronous Machine, EMPS vol.21, no. 4, 1993, pp. 473-491.
21. I. Boldea, S. A. Nasar, Electric Drives, book, CRC Press, Boca Raton, Florida, 1998.
22. M. M. Eskander, T. El-Hagri, Optimal Performance of Double Output Induction Generators WECS, EMPS, vol. 25, no. 10, 1997, pp.1035-1046.
23. A. Wallace, P. Rochelle, R.Spée, Rotor Modelling Development for Brushless Double-Fed Machines, EMPS vol. 23, no. 6, 1995, pp. 703-715.
24. O. Ojo, I. E. Davidson, PWM-VSI Inverter-Assisted Stand-Alone Dual Stator Winding Induction Generator, IEEE Trans. vol. IA-36, no. 6, 2000, pp. 1604-1610.